Ground-Based Real-Time Auto Commanding System for ISRO Advanced Technology Vehicles

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INTRODUCTION

In general, space transportation systems are expendable, resulting in huge launch cost. To meet the future challenge of low-cost access to space, the Indian Space Research Organisation (ISRO) envisaged plans to develop systems that are recoverable and reusable, besides adopting efficient propulsion systems like air-breathing rockets. Advanced Technology Vehicle (ATV) D01 is ISRO's new-generation high-performance sounding rocket vehicle offering a cost-effective test bed for demonstrating air-breathing propulsion. Experiments with scramjet technology testing are carried out at Satish Dhawan Space Centre (SDSC) SHAR, Sriharikota. For this experiment, ATV-D01 is configured as a two-stage, unguided, spinning, fin-stabilized vehicle with two protruding passive scramjet engines.

During the flight, a sounding rocket is significantly affected by wind, thrust vector misalignment, fin misalignment, and variations in motor performance and aerodynamic coefficients. In order to achieve maximum dwell time in the required Mach number (M)–dynamic pressure (q) window, an innovative flight profile is designed with two ground-based real-time event activation commands. Computation of these commands is based on the performance of the vehicle, i.e., its altitude and velocity obtained in real time by processing radar track data. This method is superior to configuring an onboard inertial system or an altimeter. Those options suffer from disadvantages such as onboard hardware complexity, increased payload weight, and associated cost. Instead, we used existing ground-based systems with sufficient redundancy to arrive at a simple, down-to-earth, cost-effective solution.

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For the first time in SDSC SHAR, a ground-based real-time commanding system is designed and developed to generate real-time event activation commands, to uplink them for sustainer ignition, and to monitor the dynamic conditions for scramjet experiment during flight. ATV-D01 was flight-tested successfully in March 2010, and real-time commanding systems were exercised for sustainer ignition, followed by environment monitoring for scramjet engine activation.

Nomenclature

T_0	Liftoff time
T_2	Real-time sustainer ignition command time
T_{Nom}	Nominal time for sustainer ignition
K	Scale factor (in seconds)
T	Flight time of vehicle (corrected for liftoff delay)
H	Altitude of vehicle obtained from track data of radars
H_m	Mean altitude obtained from Monte Carlo analysis of sensitivity study, defined as function of flight time T
H_s	Standard deviation of altitude obtained from Monte Carlo analysis of sensitivity study, defined as function of flight time T
ρ	Ambient density of atmosphere at altitude H
P	Ambient pressure (in pascals) at altitude H
V	Velocity computed from radar data
γ	Specific heat ratio
q	Dynamic pressure (in kilopascals) of the vehicle
M	Mach number
q_{ref}	Reference dynamic pressure (in kilopascals)
M_{ref}	Reference Mach number
P_{pitot}	Pitot pressure (in kilopascals) as measured at nose tip
P_{body}	Body pressure (in kilopascals)
P_{ref}	Reference pitot pressure (in kilopascals)
PR	Pitot–to–body pressure ratio

In this paper, the authors describe the design and implementation of real-time event activation command generation, uplinking methodology, and validation practices, followed by results of the ATV-D01 test flight at SDSC SHAR.

VEHICLE AND TRAJECTORY DETAILS

ATV-D01 is a two-stage, unguided, fin-stabilized vehicle with both stages comprising RH-560M solid motors [1]. The first stage, known as the booster motor, has a crucified fin system with end plates and separable spin rockets on all four fins. The second stage, known as the sustainer motor, has noncrucified fins with air-breathing modules (scramjet engines) sitting symmetrically within the larger angles. The air-breathing modules are passive, simulating external mechanical configuration (Figure 1). The booster motor burns for around 24 s (Figure 2). Then the vehicle traverses through a long coasting phase. Ignition of the sustainer is around 47 s from liftoff and is determined in real time during this coasting phase. This decision is based on radar track data of 10 Hz and is arrived at on the ground from T_0 + 34 s to T_0 + 37 s. The sustainer ignition command is uplinked at the appropriate time through the telecommand link after encryption, modulation and power amplification. Sustainer motor also burns for about 24 s. After the sustainer burnout, both the onboard and the ground-based real-time decision systems monitor the entry of the vehicle into the required M-q window (Figure 3). Mach number and dynamic pressure are calculated from onboard pitot pressure and body pressure data, as well as altitude, velocity, and meteorological data on the ground. Onboard computation is done by a data processing unit (DPU). On receiving the command from the DPU, the flight sequencer issues a sequence of commands required for the activation of the scramjet engine. Even though the active scramjet engine is not flown in this flight, sequencer

Figure 1.
ATV-D01 vehicle configured with two RH-560M modules. The sustainer is instrumented with a scramjet module.

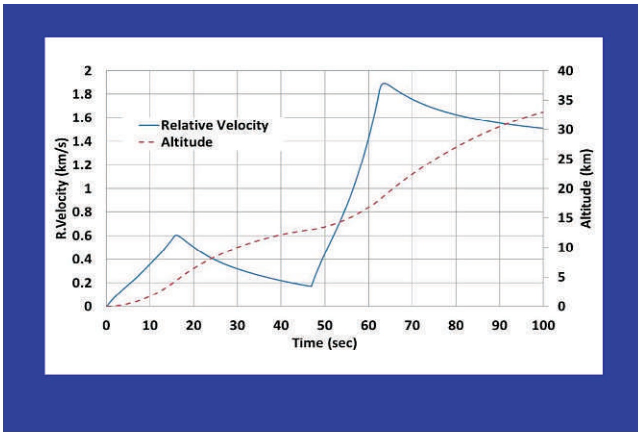

Figure 2.
Trajectory of ATV-D01: Time versus altitude and relative velocity.

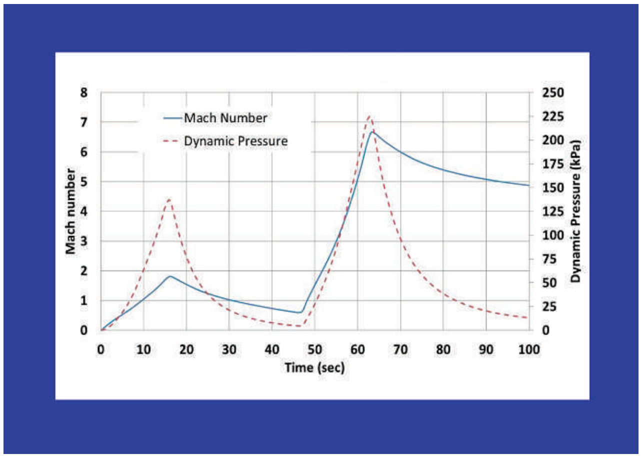

Figure 3.
Dynamics of ATV-D01: Time versus Mach number and dynamic pressure.

commands are generated as if the active scramjet engine was flown and the dwell time in the M-q window is validated using telemetry data [2].

GROUND-BASED REAL-TIME COMMANDS

Since accurate prediction of the sustainer ignition ensures maximum dwell time in the required M-q window for the scramjet experiment, performance computation using radar track data of 10 Hz is considered. Two real-time commands are configured for sustainer ignition and scramjet engine activation.

REAL-TIME SUSTAINER IGNITION COMMAND

Sustainer ignition time is computed in real time after booster burnout based on the altitude obtained by the vehicle during coasting. Precision radars track the vehicle in the transponder to obtain good-quality data, and altitude is computed at 10 Hz. Sustainer ignition time is predicted using the validated altitude from radar track data as

$$T_2 = T_{Nom} + K\,(\,H(T)-H_m(T))/H_s(T), \tag{1}$$

where T_{Nom} is the nominal time for sustainer ignition, K is the scale factor in seconds, and T is the flight time of the vehicle (corrected for liftoff delay). In addition, H is the altitude of the vehicle obtained from the track data of the radars, and H_m and H_s are the mean altitude and its standard deviation, respectively, obtained from Monte Carlo analysis of the sensitivity study; they are defined as functions of flight time T [3]. The first computational result is based on the altitude at T_0 + 34 s. The process is repeated up to T_0 + 37 s, and each time sustainer ignition time is predicted.

REAL-TIME SCRAMJET ACTIVATION COMMAND

Activation of the scramjet engine takes place when the vehicle enters the M-q window of dynamic pressure (q) of 80 ± 35 kPa and Mach number (M) of 6 ± 0.5. The M-q window is monitored in real time and the decision is made regarding the activation of the scramjet engine. This real-time decision is also based on pitot and body pressure measurements onboard the vehicle. However, the ground-based real-time scramjet activation command and the onboard decision are combined and operated.

REAL-TIME COMMAND GENERATION AND UPLINKING SYSTEM

Ground-based instrumentation for trajectory estimation of a launch vehicle consists of four precision radars, i.e., three C-band transponder-mode radars and an S-band skin-mode radar forming the major tracking network at the range. These state-of-the-art precision radars are capable of long-range tracking with an angle accuracy of 0.2 millirad. Accurate tracking of the launch vehicle by the radars is imperative for range safety, continuous evaluation of vehicle performance, and provision of a tracking aid for the acquisition or reacquisition of the vehicle during flight. So ATV-D01 is instrumented with a mini C-band transponder for aiding positive tracking.

REAL-TIME TRACKING DATA PROCESSING SYSTEM

A dual redundant distributed real-time network is configured with range safety servers to acquire and process the vehicle track data for trajectory estimation on range safety displays and to generate event activation commands on ground-based real-time commanding systems (Figure 4). The radar track data are validated, corrected for systematic errors, and filtered using a linear Kalman filter. The trajectory of the vehicle is estimated using filtered track data of all radars. The countdown time tagged to radar data is corrected for liftoff delay to obtain the flight time. These data are transmitted to real-time command generation personal computers (PCs).

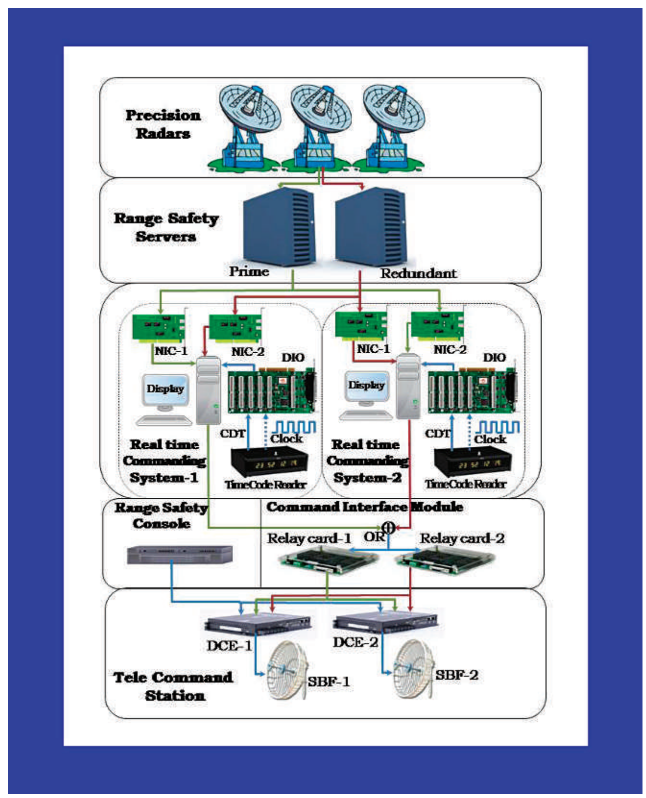

Figure 4.
Schematic diagram depicting the real-time command generation and uplinking to the vehicle. This logic is implemented on a dual redundant distributed computer network consisting of range safety servers, real-time commanding systems, and telecommand uplinking systems. Real-time commands are transmitted to telecommand systems via a command interface module, which in turn transmits them through the DCE after encryption, modulation, and power amplification.

REAL-TIME COMMAND GENERATION, DISPLAY, UPLINKING, AND LOGGING SYSTEM

The two-chain real-time command generation, display, uplinking, and logging system is developed on Pentium PCs interfaced with range safety servers (prime and redundant), a timing station and a telecommand system. Each PC acquires track data–based filtered state vectors with the flight time at 10 Hz from the range safety servers on two independent chains through two Ethernet interface cards. Altitude (in kilometers), relative velocity (in kilometers per second), and position azimuth (in degrees) are computed from filtered state vectors individually. Validated track data of transponder mode precision radars are only considered for real-time command generation.

Interradar comparison is carried out to identify valid radar sources. The precision transponder mode radar source with more duration of continuous tracking is selected as the reference radar during a processing cycle of 100 ms. Altitude and position azimuth of the reference radar are compared with those of other radars. The radar sources matching within 200 m in altitude and 2° in position azimuth are considered.

If the reference radar does not match other radars, then comparison is carried out considering the high-priority radar as the reference radar. This comparison is continued by keeping the next-priority radar as the reference radar until matching sources are identified. The priority radar source is considered if none of the preceding radars are matching.

For every processing cycle of 100 ms, average altitude and average relative velocity are computed among valid and matching sources. Sustainer ignition time (T_2) is predicted using average altitude (H) from $T_0 + 34$ s of flight time onward up to the sustainer ignition command computation window-out time and is monitored for its trend (Equation 1). Trend monitoring of T_2 is carried out by moving average methodology.

COMPUTATION METHODOLOGY FOR SUSTAINER IGNITION TIME (T_2)

Sustainer ignition time (T_2) is predicted from T_0 + 34 s onward. It is checked against sustainer ignition command window-in and window-out times. For the first three cycles, the values are updated in an 11-sample array and the average value is obtained. For the fourth cycle onward, T_2 values are checked against the previous averaged value ±0.25 s before updating and the latest average value is obtained after every update. After 11 cycles, the average of the latest 11 values is considered for validation. This continues until the sustainer ignition command computation window-out time. At the sustainer ignition command computation window-out time, the latest validated sample is considered for T_2.

Methodology used to arrive at the sustainer ignition time (T_2) is expressed in the following cases. A comprehensive set of cases are considered ensuring a positive uplinking of the sustainer ignition command (Table 1).

Where

$RTD1_{win}$	Sustainer ignition command window-in time
$RTD1_{wout}$	Sustainer ignition command window-out time

COMMAND UPLINKING METHODOLOGY

After T_2 is finalized, the sustainer ignition command is uplinked when the flight time reaches the sustainer ignition time. Real-time commanding systems are interfaced with the telecommand system via the command interface module (Figure 4). This module is realized with four DB-24RD relay cards with independent power supplies on each chain. The interface between the real-time commanding system and the relay cards in the command interface module is by means of 144-bit opto-22 pin digital input/output (DIO) card. The real-time commanding system and its interface with telecommand system are configured to ensure reliable and accurate uplinking of real-time commands to the vehicle. Each real-time commanding system acquires countdown time and a 100-pps interrupt signal from the master timing station through a DIO card. The real-time logic is checked from "window-in" onward. When the flight time matches the sustainer ignition command time (T_2), the sustainer ignition command from both chains is automatically combined and posted to the command interface module. The uplinking delay and onboard execution delay are considered while posting the command.

Table 1.

Sustainer Ignition Times

No.	Cases	Sustainer Ignition Command Uplinking Time
1	$RTD1_{win} < T_2 < RTD1_{wout}$	T_2
2	$T_2 < RTD1_{win}$	$RTD1_{win}$
3	$T_2 > RTD1_{wout}$	No command from ground and onboard sequencer commands at $RTD1_{wout}$
4	No track data case	T_{Nom}
5	Failure of telecommand link / no command from ground	Onboard sequencer commands at $RTD1_{wout}$

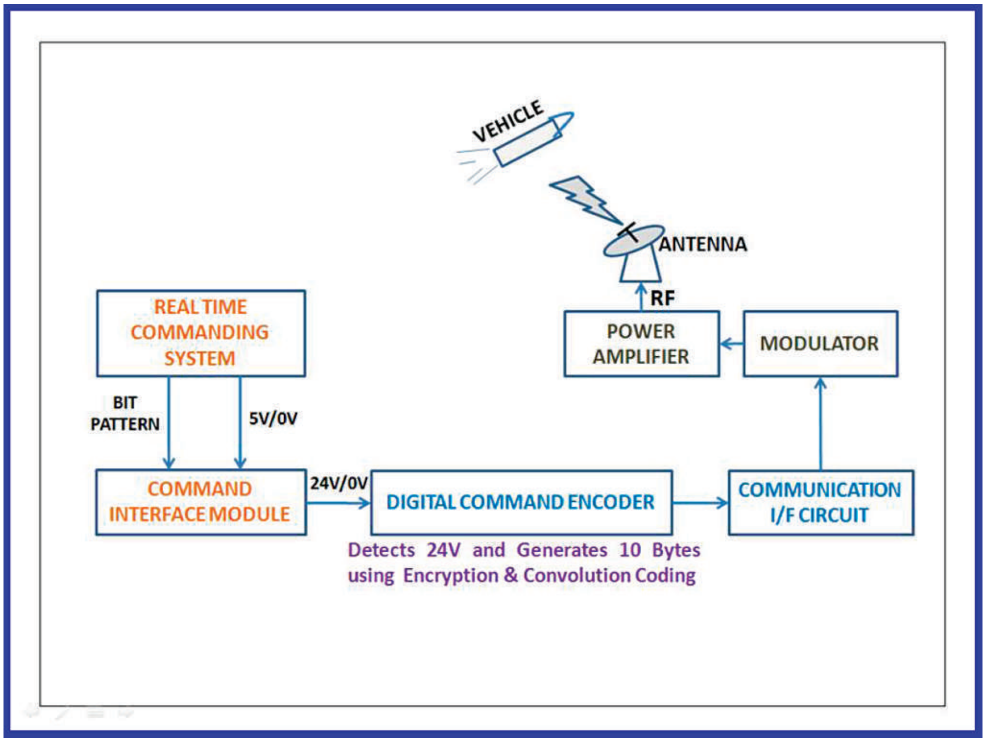

Figure 5.
Schematic diagram depicting the flow of the command from the real-time commanding system to the telecommand antenna.

The sustainer ignition command is posted to the command interface module and latched for 2 s. The digital command encoder (DCE) detects the 24-V signal from the command interface module and generates a 10-byte code after encryption and convolution coding for error detection and correction. This code is frequency-shift keying (FSK) modulated by the communication interface. The modulator carries out frequency modulation on the FSK-modulated code using a 434-MHz ultrahigh-frequency carrier. After power amplification to 1 KW, the two-chain telecommand system uplinks the encrypted command to the vehicle (Figure 5). After 2 s, the safe command is posted and latched to facilitate decision making by the range safety officer. Real-time command posting is configured so that the range safety officer can override posts in case of any exigency.

SCRAMJET EXPERIMENT ACTIVATION COMMAND

The scramjet experiment is carried out in the specified M-q window. After burnout of the sustainer, the command for fuel valve opening needs to be executed once the vehicle enters the required M-q window. Liquid hydrogen valve opening is nothing but the start of the scramjet experiment.

Scramjet activation is based on either an onboard command or a ground-based command. The onboard decision is arrived at based on pitot pressure and body pressure data. The decision on the ground uses radar track data and atmospheric data. These two commands are independent of each other. The specially designated command for sustainer ignition is also used for the scramjet activation command.

In the first flight, uplinking of the real-time scramjet activation command is not configured, but the command for fuel valve opening is based on the onboard decision. However, the ground-based command is generated and monitored. Data are continuously logged from ignition of the sustainer until real-time scramjet activation command generation for postflight study. The scramjet activation window lies between $T_2 + 21$ s and $T_2 + 25$ s, where T_2 is the sustainer ignition time.

The sequencer issues the sequence of commands for scramjet engine activation on reception of the flag from the DPU. The DPU issues one pattern as the flag when the computation results using pitot and body pressure data sense the entry of the vehicle into the specified M-q window. It generates another pattern as the flag at the relay closure of a specially designated ground-based command. The sequencer issues the scramjet activation sequence on receiving either of these flags. In the absence of these flags, the DPU issues the sequence at window-out time.

Ground-Based Scramjet Activation Command Computation

Mach number and dynamic pressure are computed from the radar data and atmospheric data. For every processing cycle, the average altitude and average relative velocity are computed using valid and matched tracking sources. Dynamic pressure and Mach number are computed using the following equations [3].

Dynamic pressure (q) is expressed as

$$q = \rho V^2 / (2 \times 1000) \qquad (2)$$

and Mach number (M) is expressed as

$$M = V \sqrt{(\rho / \gamma P)}, \qquad (3)$$

where ρ is the ambient density of the atmosphere at altitude H, P is the ambient pressure (in pascals) at altitude H, V is the velocity computed from the radar data, H is the altitude computed from the radar data, and γ is the specific heat ratio.

Atmospheric data are taken from the Indian Standard Atmospheric model used by the meteorology facility at SDSC SHAR. The following equation is used for checking entry into the required M-q window. The ground-based real-time commanding system verifies the following computation:

$$(q < q_{ref}) \text{ OR } (M < M_{ref}), \tag{4}$$

where q is the dynamic pressure (in kilopascals) of the vehicle, M is the Mach number, q_{ref} is the reference dynamic pressure (in kilopascals), and M_{ref} is the reference Mach number.

When the logic is satisfied (Equation 4), the ground-based real-time system issues the command and it is monitored.

Onboard Scramjet Activation Command Computation

Scramjet activation command generation logic is initiated 21 s after sustainer ignition T_2. Onboard the vehicle, entry into the M-q window is monitored using pitot pressure and body pressure [3]. It is expressed as

$$\{P_{pitot} \leq P_{ref}\} \text{ OR } \{(P_{pitot} / P_{body}) \leq PR\}, \tag{5}$$

where P_{pitot} is the pitot pressure (in kilopascals) as measured at nose tip, P_{body} is the body pressure (in kilopascals), P_{ref} is the reference pitot pressure (in kilopascals), and PR is the pitot–to–body pressure ratio.

RESULTS AND DISCUSSION

PREFLIGHT SIMULATIONS

Simulated trajectory data for the precision radars at 10 Hz are generated, and real-time command generation and its uplinking are verified. The real-time commanding system is exercised end to end to validate the hardware elements, software elements, links, and human interface. A number of nominal and failure mode conditions for real-time command generation are exercised, and transmission to the telecommand system through the command interface module, followed by uplinking to the vehicle onboard, is tested and evaluated [4]. During these simulations, flight hardware has been used to establish the uplinking delay and the onboard command execution delay.

TEST FLIGHT RESULTS

During the test flight, the sustainer ignition command is computed and uplinked at 44.52 s after liftoff. The scramjet activation command is generated and monitored for the entry of the vehicle in the requisite M-q window. It is observed that the M-q window occurred as expected between 64.9 and 72.3 s after liftoff (Figure 6). ATV-D01 is also instrumented with S-band telemetry. Onboard vehicle telemetry data pertaining to stage propulsion, body pressures, pitot pressures, temperatures, longitudinal and lateral accelerations, telecommand system monitoring parameters, etc., are transmitted to ground stations at 2 Hz. These data are processed and displayed to validate real-time commands.

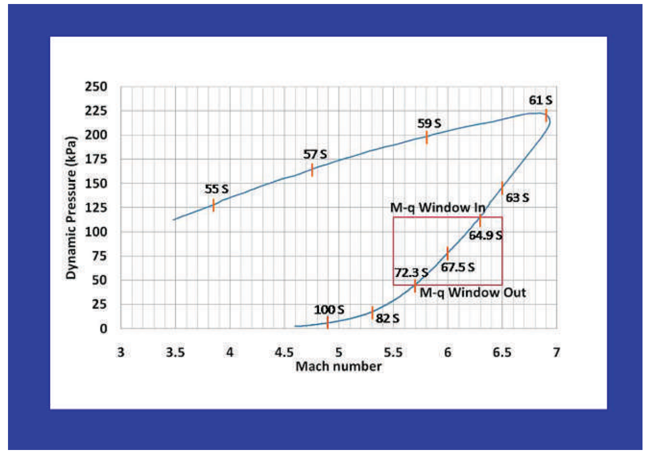

Figure 6.
Experimental results of the scramjet activation times: Mach number versus dynamic pressure. The hypersonic limits of the velocity and dynamic pressures requisite for the experiments are attained.

CONCLUSION

Real-time command generation and uplinking for sustainer ignition, followed by monitoring of Mach number versus dynamic pressure for the scramjet experiment, has been successfully implemented at SDSC SHAR. The sustainer is ignited using the real-time command uplinked from the telecommand system. Mach number versus dynamic pressure parameters are monitored for scramjet activation. The dwell time attained in the M-q window is 7.4 s from $T_0 + 64.9$ s to $T_0 + 72.3$ s against a nominal of 9.2 s, and it is quite encouraging. These values closely matched those obtained from onboard pitot pressure and body pressure [5]. Real-time decision making using the existing ground-based systems proved to be effective in carrying out this scramjet experiment. As the backdrop of this success, this methodology can be effectively used for ground control of various experiments. The ascent of the vehicle in direct vertical profile makes it an excellent platform for space research. The ATV can provide 10 min of microgravity at levels better than 100 µg, which makes it the most suitable platform for microgravity, physical, and biological experiments [6]. In addition, an automated ground-control and command system can be developed along these lines for range safety decision making [7]. Autogeneration of such a command supplements the human element and is complementary to the onboard autodestruct system.◆

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Coming up in the August 2014 issue, the 2013 IEEE AESS Pioneer Awardees, Kam Y. Lau, from the University of California at Berkley, and George F. Lutes, from the NASA Jet Propulsion Laboratory, tell the story of the events leading up to the effort for which they received the award. They received the Pioneer Award for "Ultra-Stable RF-Over-Fiber Transport Enables NASA Ground-Based Deep Space Tracking Antenna Arrays and Space-Borne Earth Mapping Radar." The story begins in the Mohave Desert North of Los Angeles in Southern California in a small valley near the ghost town of Goldstone northwest of Barstow, where "big steerable parabolic dish antennas rise from the desert floor" and workers deal with vinegaroons and rattle snakes in a landscape of sagebrush and Joshua Trees. Stay tuned for the rest of their tale in August.

Fiber cables laid 1.5 m underground at the Goldstone Deep Space Communications Complex in the Mojave Desert